THE ZEEMAN EFFECT ON THE SUN*

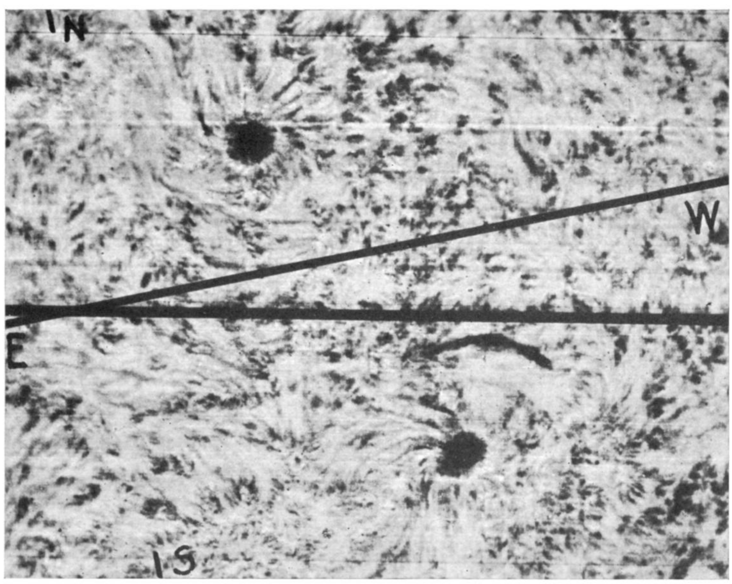
By Adriaan van Maanen

In his splendid monograph, "Researches in Magneto-Optics,"[1] Zeeman begins the eighth chapter with the following words: "In discoveries of optics we may always cherish the hope that they will lead ultimately to applications to astronomy."

For the Zeeman effect this hope was realized within a dozen years, but its applications up to this time have been confined to only one astronomical body, *viz.*, the Sun. It is true that a few other instances of the doubling of spectral lines have been observed which could possibly be attributed to a magnetic field: Wright[2] made an attempt to detect polarization in the multiple bright lines of *o Ceti;* Adams and Kohlschütter[3] did the same in the case of the complex hydrogen bands in *Nova Geminorum* No. 2; and Merrill[4] tested the double bright Hβ line in γ *Cassiopeiæ* and in b^2 *Cygni.* Definite evidence of a magnetic field was not obtained in any case. Slipher[5] announced in 1915 the doubling of N_1, N_2, N_3, Hβ and Hγ in the *Crab* nebula with a maximum distance of the components of 40 A, and in 1918 Campbell and Moore[6] published the appearance of double lines in the spectra of ten planetary nebulæ; as their experiments made on N. G. C. 7662, in an attempt to detect polarization in the components furnish strong negative evidence, they conclude, however, that the phenomenon is not a simple Zeeman effect. On the other hand, for the Sun the Zeeman effect has now been established with great certainty. Hale's important discovery of magnetic fields in sun-spots was made soon after the introduction of certain improvements in red-sensitive plates by Wallace.[7] The spectroheliograph had already made it possible to photograph the Sun's image in the light of a single spectral line, the lines used being ordinarily H and K of calcium and the Hδ, Hγ and Hβ line of hydrogen. In 1908 the red-sensitive plates, which enabled Hale and Ellerman to use the high-level Hα line,

*Translated from the Dutch Journal *"Physica,"* the number of which for Oct. 31, 1921, was dedicated to Dr. G. Zeeman, in recognition of his discovery, 25 years ago, of the separation of spectral lines in a magnetic field.

[1] *MacMillan and Co.,* London, 1913.
[2] *Lick Obs. Bulletin,* **6**, 60, 1910.
[3] *Mt. Wilson Contr.,* No. 62, 1912.
[4] *Lick Obs. Bulletin,* **1**, 174, 1913.
[5] *Nature,* **95**, 185, 1915.
[6] *Publ. of the Lick Observatory,* **13**, 178, 1918.
[7] *Astroph. Jour.,* **26**, 299, 1907.



Sun-spots and hydrogen flocculi in light of the Hα line, showing right and left handed vortices, October 7, 1908.

PLATE IV.

soon gave some very interesting results. Immense vortices were found surrounding the sun-spots (Plate IV), and this led Hale to the hypothesis that a sun-spot is a solar storm, comparable with a terrestrial tornado. This idea soon found confirmation in the fact that a large cloud of hydrogen, which had hung for several days on the edge of one of these vortices, was suddenly swept into the spot with a velocity of about 60 miles per second.

It was already known that hot bodies emit electrons. The high temperature of the Sun must necessarily produce a considerable number of free electrons in the solar atmosphere, and when these are swept around in a vortex movement they form a magnetic field; the spectral lines must then show a Zeeman effect. Lockyer, in 1866, had already observed that some of the lines in a sun-spot spectrum were widened; Young and W. M. Mitchell observed that some of the lines were even double, but Mitchell refers to these doublets as "reversals." The great dispersion of the 60-foot tower telescope, built in 1908, enabled Hale to study the components of the doublets for polarization. On June 25, 1908, Hale obtained some photographs in the third order of the region $\lambda6000$ to $\lambda6200$ of a spot not far from the center of the Sun's disk. Above the slit of the spectograph were placed a Fresnel rhomb and a Nicol prism; the plates clearly showed a reversal of the relative intensities of the components of the spot doublets when the Nicol prism was rotated over an angle of 90°. Moreover, many of the widened lines were shifted in position by a rotation of the Nicol, indicating that light from the edges of the lines was circularly or elliptically polarized. The displacements were similar to those discovered by Zeeman in a magnetic field when the lines of force were parallel to the line of sight. A spot near the Sun's limb soon enabled Hale to determine that the observed effect in that case was analogous to Zeeman's observations at right angles to the lines of force; he therefore concluded that the sun-spots contained magnetic fields and that the lines of force were directed nearly radially towards the center of the Sun. Later observations on spots have fully corroborated his original results. From a comparison of the separation of the components of certain lines in sun-spots with the separation in laboratory experiments for known field-strength, the intensity of the field in sun-spots can be derived;

in some cases it has been found to be as high as 4500 gausses.

Since the construction of the 150-foot tower telescope, this instrument has been used regularly for the study of the Zeeman effect on the Sun. The tower (Fig. 1) is of double skeleton construction, one inside the other; the two towers, with the members nowhere touching, stand on separate concrete piers. In this way the necessary steadiness has been secured notwithstanding the great height. The outer tower, carrying the revolving dome, which can, therefore, be turned around during the observations without jarring the inner tower and blurring the solar image, also protects the inner tower from being shaken by the wind. An elevator makes it possible to reach the top. The accompanying diagram shows a cross-section of the instrument; in order not to overcrowd the picture the structure of the inner tower has been omitted except at the lower right hand.

The optical parts are mounted at the top of the inner tower; a cœlostat mirror of 19 inches diameter and a thickness of 13 inches sends a beam of sunlight to a second flat mirror 15 inches in diameter and 11 inches thick, from which it is reflected vertically downward to a 12-inch objective of 150 feet focal length. In this manner an image of the Sun of more than 16 inches diameter is formed in the observing-room at the foot of the tower. The slit of the spectrograph is about 3 feet above the floor; passing through this slit, the light descends to a collimating lens of 75 feet focal length mounted near the bottom of the pit; directly below this lens is a grating ruled by Michelson and containing about 15,800 lines to the inch; from the grating the light is returned through the collimating lens, which serves also as a camera objective, and forms an image of the spectrum on a photographic plate mounted beside the slit of the spectrograph. Forty inches of spectrum can be photographed with a single exposure.

The cœlostat and second flat mirrors have been made unusually thick in order to avoid, or at least reduce, the changes in focal length of the mirrors due to the heating effect of the sunlight. For the same purpose both mirrors are surrounded on the sides and on the bottom by water-jackets in which water of a nearly constant temperature can be kept circulating by a

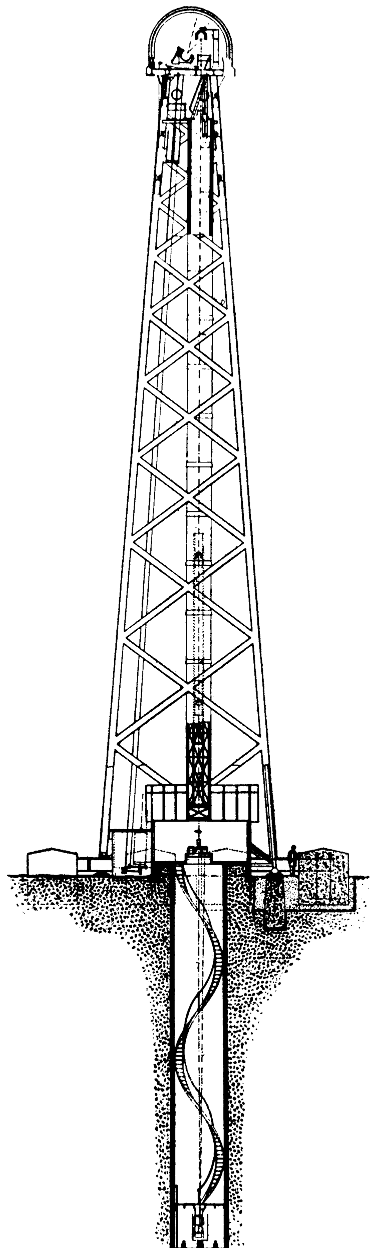


FIG. 1. Cross-section of the 150-foot tower telescope.

pumping device. These precautions have proved to be extremely useful.

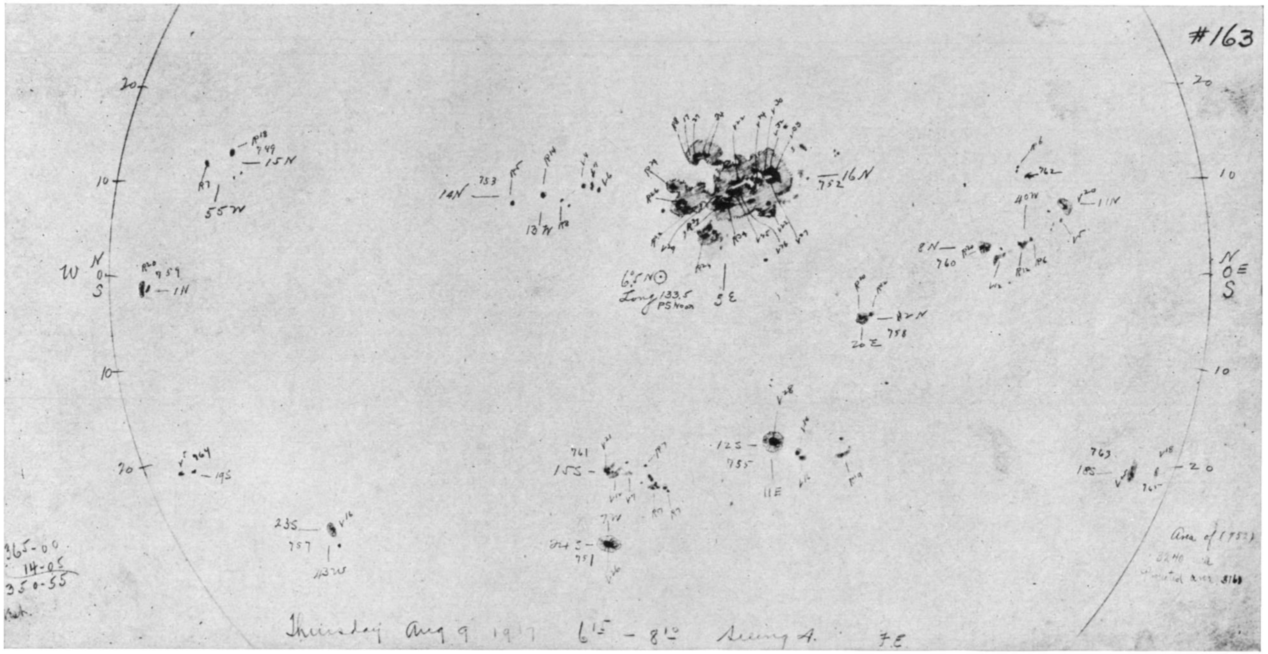
From the base of the tower near the slit of the spectrograph the observer can, by electrical devices, make practically all the necessary changes in the instrument. From there he can control the fast and slow motions of the cœlostat and second flat mirrors; he can focus the objective, start the cœlostat clock and the pump for circulating the water, and turn the dome. From the same place he is able also to focus the auto-collimating lens, tilt the grating, and rotate it. In this way the instrument, once ready for use, does not need, during the day's work, any readjustment which requires the observer to go either to the top of the tower or the bottom of the pit.

For the study of polarization phenomena a Nicol prism is placed just over the slit of the spectrograph; over this is mounted a compound quarter-wave plate, so constructed that the principal sections of the successive mica strips (2 mm. wide) are normal to each other and form angles of 45° with the slit.

With this apparatus the polarity and the intensity of the magnetic field are determined for every sun-spot; a daily map is made of the Sun's image, showing all visible spots (Plate V); the polarity is indicated by V or R, accordingly as the violet or the red component of the Zeeman triplet $\lambda 6173.553$ is transmitted by a given strip of the quarter-wave plate. The strength of the field is measured with a parallel-plate micrometer and the readings are recorded in degrees of inclination of the glass plate (2 mm. wide); since in the second order of the spectrum for the line $\lambda 6173$, one degree corresponds approximately to 100 gausses, the observer places near every spot the measured displacement in degrees, indicating the field in units of 100 gausses.

The determination of the polarities of hundreds of spots has enabled Hale and Nicholson to classify the sun-spots as unipolar, bipolar and of mixed polarity. A full discussion of the results of this investigation would lead too far; we may, however, mention the principal results.[8] About 60 per cent of all sun-spots are binary groups, the single or multiple members of which are of opposite magnetic polarity; unipolar groups usually exhibit some of the characteristics of bipolar groups. Before the sun-

[8] *Mt. Wilson Contr.*, No. 165, 1919.



Sketch showing daily record of observations of sun-spot polarities, August 9, 1917; the numbers 749 to 764 indicate the preliminary numbers of the spots; near each spot is given the position, the polarity, and the field-strength in 100 gausses.

PLATE V

spot minimum of 1913, the magnetic polarity of unipolar spots and of the preceding members of bipolar spots was positive in the southern and negative in the northern hemispheres of the Sun, but since that minimum these signs have been reversed.

A map of the sun-spot spectrum covering the region from $\lambda 3900$ to $\lambda 6600$ has lately been prepared by Ellerman, who used the polarizing apparatus described above. On this map, which has been reproduced on a scale of 1A=1 cm, more than 5000 lines show the influence of a magnetic field in the spots; the material is under investigation and undoubtedly contains most valuable data for the theory of sun-spots.

The discovery of magnetic fields in sun-spots led Hale to the question whether the Sun as a whole is a magnet. The structure of the corona, as observed at total eclipses, points strongly in this direction; Bigelow[9], in 1889, had shown the strong resemblance between the coronal streamers and the lines of force of a spherical magnet. For this investigation the same polarizing apparatus was used. A priori we could not expect a strong enough magnetic field to cause the lines to show anything more than a widening; a large dispersion was therefore desirable and practically all the plates for this investigation were accordingly taken in the third order of the spectrum, where 1A covers about 5 mm.

The necessary formulæ were derived by Seares[10]. The polarizing apparatus transmits the light of a normal triplet in such a way that the intensities of the three components in one set of alternate strips of the quarter-wave plate are:

$$R=\tfrac{1}{4}\,(1+\cos\gamma)^2;\ M=\tfrac{1}{2}\sin^2\gamma;\ V=\tfrac{1}{4}\,(1-\cos\gamma)^2 \qquad (1)$$

In the other set the intensities are:

$$R^1=\tfrac{1}{4}\,(1-\cos\gamma)^2;\ M^1=\tfrac{1}{2}\sin^2\gamma;\ V^1=\tfrac{1}{4}\,(1+\cos\gamma)^2 \qquad (2)$$

where γ is the inclination of the lines of force to the line of sight. For $\gamma=0°$, $R=V^1$, while all other components are zero; this corresponds to a maximum displacement in two successive strips. For $\gamma=90°$ the distribution of the intensities is symmetrical and equal for successive strips. If H is the field-strength in gausses and C the distance between the outer com-

[9]Bigelow, *The Solar Corona*, Smithsonian Institution, 1889.
[10]*Mt. Wilson Contr.*, No. 72, 1913.

ponents for a field of intensity of 1 gauss, then the displacement in successive strips will be

$$\Delta = C\,H \cos\gamma \quad (3)$$

Supposing that the Sun is a uniform magnetized sphere whose magnetic equator passes through the observer, we will find for points on the central meridian

$$k\,\Delta = 3 \sin 2\,\phi \quad (4)$$

where ϕ is the latitude with respect to the magnetic equator, $k = 4/C\,Hp$, and Hp is the field-strength at the magnetic pole.

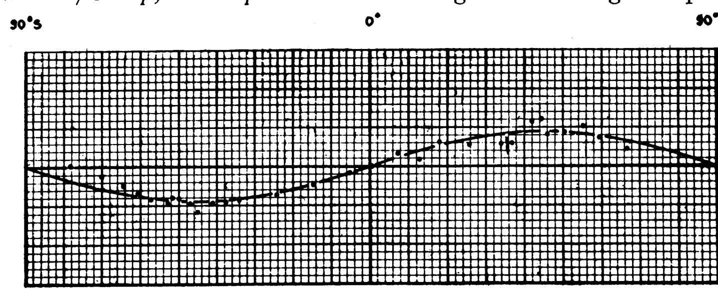


Fig. 2

Mean curve of displacements, including 468 observations of the lines λ5812,λ5828 and λ5930. Vertical scale: 1 division = 0.001mm.

The displacement curve will be a sine curve with a maximum and a minimum for $\phi = 45°$.

The first spectra taken by Hale and Ellerman were measured by Miss Lasby; out of 30 lines only three were found which showed a measurable displacement, *viz.*, λ5812.139 (Fe, 0); λ5828.097 (?, 0), and λ5929.898 (Fe, 2); the displacements for these lines, however, agreed as closely as could be expected with a sine curve of the form of equation (4). A large amount of material seemed necessary in order to establish the reality of the magnetic field. Several series of plates showing the three lines were accordingly taken by Ellerman and measured by van Maanen. The resulting displacements (including 468 observations) were arranged in order of decreasing latitude and combined into the normal points, shown in Fig. 2; the agreement of these with the theoretical curve determined by the average of the displacements for $\phi = 45°$ is as good as might be expected, when one keeps in mind the smallness of the measured quantities, which, at maximum, is about 0.001 A, or 0.005 mm.

When the existence of the general magnetic field was fairly proved by these results, an investigation was started to discover more lines showing analogous displacements. For this purpose lines were chosen which either in the laboratory or in sun-spots had shown a considerable separation of the components. On account of the difficulties in measuring, lines brighter than 5 or fainter than 0 had to be excluded. For 30 out of 46 lines investigated, displacements corresponding to a magnetic field were found distributed over the different elements as follows:

Fe, 11; Cr, 8; Ni, 4; V, 5; Ti, 1.

One line has not yet been identified.

The field-strength was next determined for each line which showed for the different elements a correlation of field-strength and intensity. As the intensities are as a whole a function of level in the solar atmosphere, it was obvious that a search for a relation between field-strength and level might reveal some interesting results. A thorough discussion of the material at

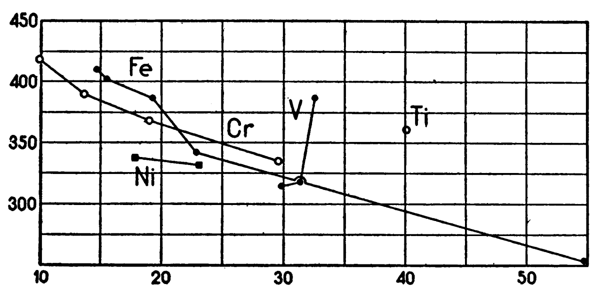


FIG. 3

Relation between field-strength and level in the sun's atmosphere. The elevations (ordinates) are in kilometers, the field-strengths (abscissæ) in gausses.

hand was made by Seares[11]; this showed that the strength of the general magnetic field decreases with increasing elevation in the solar atmosphere. S. A. Mitchell's[12] observations of the flash spectrum were used to construct the diagram in Fig. 3, showing the variation of field-strength with level in the Sun's atmosphere; the ordinates represent the elevations in kilometers, the abscissæ the field-strengths in gausses. With the exception of

[11] *Mt. Wilson Contr.*, No. 148, pp. 32-43, 1918.
[12] *Publ. McCormick Obs.*, 2, Part 2, 1913.

one titanium and one vanadium line, all points lie closely on a curve, which for level 250 km gives $Hp = 55$ gausses; for level 420 km, $Hp = 10$ gausses. It seems that only lines in a very shallow layer show influence of the magnetic field large enough to be detectable by the present means of attack.

Finally, an effort was made to locate the poles of the magnetic field; from the small asymmetry of the sine curves derived thus far, it had already become evident that the magnetic poles could not be situated very far from the poles of rotation. For this investigation equation (4) takes the form:

$$k \, \Delta = A \cos i + B \sin i \cos \lambda$$
$$A = 3 \sin (2 \phi - D) + \sin D;$$
$$B = 3 \cos (2 \phi - D) + \cos D$$

in which ϕ represents the heliographic latitude, λ the longitude of the north magnetic pole, i the inclination of the two axes, and D the angle of the observer above the Sun's equatorial plane.

Three lines were selected which on account of their intensity and displacement made them desirable for an investigation necessarily laborious. On 74 days between June 8 and September 25, 1914, Ellerman secured plates ranging over a latitude from about 50° north to 50° south which were measured by van Maanen. From the displacements Seares has derived the following results:

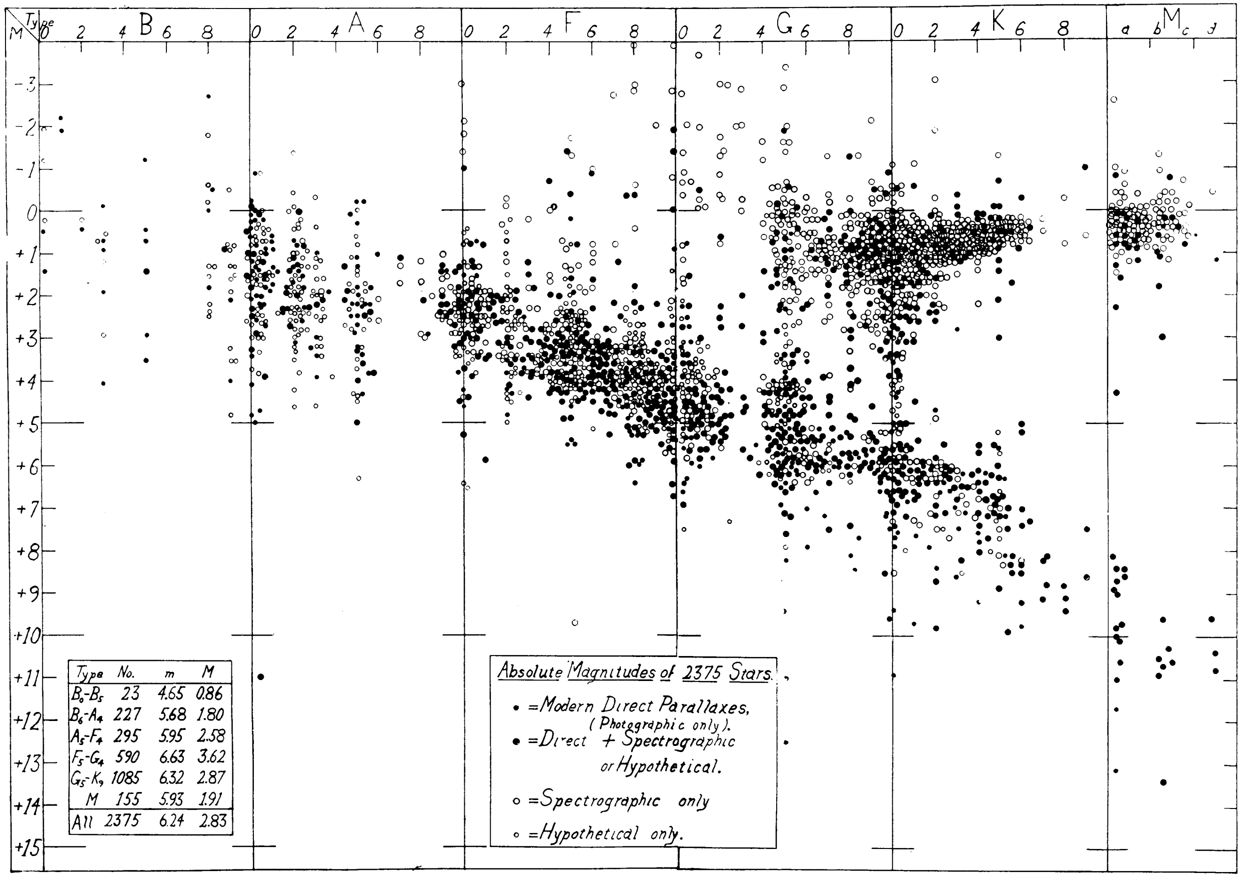
$$i = 6^{\circ}.0 \mp 0^{\circ}.4$$
$$P = 31.52 \mp 0.28 \text{ days}$$
$$t_0 = 1914 \text{ June } 25.38 \mp 0.42 \text{ days}$$

A second series of plates, taken from September 2 to 29, 1916, shows that the period of 31.52 days was close to the truth. For the 26 periods intervening between the two series, the difference is less than three days, or less than 0.12 day per period, which is well within the limit of the probable error.

The lack of sun-spots in the summer of 1920 enabled Ellerman, Nicholson, and Benioff to secure a third series of plates from July 1 to September 22. These plates, however, have not yet been measured, but they undoubtedly contain the data for a very accurate determination of the period, if constant.

I hope that I have shown of how much importance Zeeman's discovery of the separation of spectral lines in a magnetic field has already been in the development of solar physics. That his discovery ultimately will find application in other branches of astronomy is hardly to be doubted.

Pasadena, September, 1921.


Type
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a b c d
Absolute Magnitudes of 2375 Stars.
• =Modern Direct Parallaxes, (Photographic only).
● =Direct + Spectrographic or Hypothetical.
○ =Spectrographic only
∘ =Hypothetical only.
Type No. m M
B_0-B_5 23 4.65 0.86
B_6-A_4 227 5.68 1.80
A_5-F_4 295 5.95 2.58
F_5-G_4 590 6.63 3.62
G_5-K_9 1085 6.32 2.87
M 155 5.93 1.91
All 2375 6.24 2.83

PLATE VI.